

## The water intensity of the transitional hydrogen economy

This article has been downloaded from IOPscience. Please scroll down to see the full text article.

2007 Environ. Res. Lett. 2 034007

(<http://iopscience.iop.org/1748-9326/2/3/034007>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 128.83.56.94

The article was downloaded on 28/05/2013 at 19:25

Please note that [terms and conditions apply](#).

# The water intensity of the transitional hydrogen economy

Michael E Webber

Center for International Energy and Environmental Policy, Jackson School of Geosciences,  
University of Texas at Austin, USA

and

Department of Mechanical Engineering, Cockrell School of Engineering, University of Texas  
at Austin, USA

E-mail: [webber@mail.utexas.edu](mailto:webber@mail.utexas.edu)

Received 7 March 2007

Accepted for publication 6 September 2007

Published 20 September 2007

Online at [stacks.iop.org/ERL/2/034007](http://stacks.iop.org/ERL/2/034007)

## Abstract

The water intensity of the transitional hydrogen economy is analyzed by quantifying the direct and indirect water requirements to annually manufacture 60 billion kg of hydrogen partly by thermoelectrically powered electrolysis. It is determined that up to 143 billion gallons of water would be directly consumed as a feedstock, with a total consumption including evaporation of cooling water at power plants of 0.5–1.7 trillion gallons annually. Total water withdrawals for thermoelectric cooling (most of which is not consumed) are expected to increase by 27–97% from 195 000 million gallons/day today, depending primarily on the aggregate efficiency of electrolyzers that will be in place and the portion of hydrogen that is produced by thermoelectrically powered electrolysis. On a per unit basis, thermoelectric power generation for electrolysis will on average withdraw approximately 1100 gallons of cooling water and will consume 27 gallons of water as a feedstock and coolant for every kilogram of hydrogen that is produced using an electrolyzer that has an efficiency of 75%. Given that water withdrawals have remained steady for decades, this increase in water use represents a significant potential impact of the hydrogen economy on a critical resource, and is consequently relevant to water resource planners. Thus, if minimizing the impact of water resources is a priority and electrolysis becomes a widespread method of hydrogen production, hydrogen production would need to be from hydrogen production pathways that do not use much water (such as wind or solar), or effective water-free cooling methods (e.g. air cooling) will need to be developed and widely deployed.

**Keywords:** hydrogen economy, water, alternative energy, electrolysis, energy systems, energy policy

## 1. Introduction

The ‘hydrogen economy,’ a term used to describe a future American energy system that widely uses hydrogen as a fuel for transportation and stationary power, has been the subject of much popular commentary, discussion, analysis, and federal research investment. The hydrogen economy’s potential got a significant boost from President Bush’s 2003 State of the Union speech, during which he announced a large-scale R&D program to develop the necessary scientific and engineering advances to kickstart the transition from petroleum

to hydrogen [1]. Subsequently, the Department of Energy has invested more than \$900 million on projects related to the hydrogen economy [2]<sup>1</sup>.

Since then, many articles that analyze the hydrogen economy’s opportunities and challenges have been published in popular and scientific media [3–9]. The most authoritative report on the hydrogen economy’s prospects in the United

<sup>1</sup> The total of just over \$900 million includes more than \$610 million in appropriations from FY04 (fiscal year 2004) to FY07 and an administration request of more than \$289 million for FY08.

States was prepared in 2004 by the National Research Council (NRC), which examined the different opportunities and barriers to broad-based market penetration of hydrogen as a fuel for transportation [9]. Among the report's many conclusions is that the transition to a predominantly hydrogen-based economy will take several decades, with ultimate demand for hydrogen possibly exceeding 100 billion kg annually after 2050 when the hydrogen economy is fully scaled up. This manuscript examines the possible water intensity for hydrogen production during the transition period at a point 30 years from today (2037).

The vast body of scientific literature establishes that there are many different possible pathways for hydrogen production at different stages of technological maturity, including chemical conversion, thermolysis, electrolysis, photochemical, biological, and so forth. Each pathway has its own technical, environmental and economic merits and challenges. Though analyses of the various hydrogen production pathways, fossil fuel requirements, carbon emissions and other aspects have been rigorously considered by the peer-reviewed literature, one aspect that has received scant attention is the water intensity of the hydrogen economy. For example, the US Department of Energy's recent posture, vision and roadmap documents make no mention of the hydrogen economy's impact on water resources [2, 10–12]. The NRC's report, despite its broad-based look at the hydrogen economy, admittedly 'did not examine the impacts on water' [9]. Some have considered the direct water use by the hydrogen economy, but the calculations were either preliminary or did not fully consider the indirect water requirements [3, 7, 13, 14]. Though the water intensity of biofuel production has been raised as a concern worthy of further evaluation [14–16], until now the water intensity of hydrogen production has not been flagged as an issue of concern.

This manuscript seeks to fill that analytical gap by considering the water intensity of the transitional hydrogen economy—including indirect uses of water—at a point 30 years into the future as a way to inform decision-makers about impacts on this critical and often unconsidered resource as we approach the beginning of the transition from petroleum to hydrogen.

## 2. Analytical scope: hydrogen production by electrolysis of water

As noted before, hydrogen can be produced in various ways, including gasification, electrolysis, reforming hydrocarbons, and so forth. In the long term, some of the most promising routes to efficient, large-scale production of hydrogen employ techniques such as nuclear thermochemical splitting of water, or gasification of coal or biomass. Despite the economies of scale and potential efficiencies these approaches offer, the NRC's report concludes that because of the vast amounts of capital expenditures required for these types of facilities, they are unlikely to play a significant role in hydrogen production for several decades because they first need vast infrastructure systems (e.g. dedicated distribution systems) to economically justify their construction [9].

Though scaling up a hydrogen centralized infrastructure system to meet a sizable portion of energy consumption in the US is expected to require decades and large investments in infrastructure, approximately 9 billion kg of hydrogen is already produced on-site annually in the US for the fertilizer and petrochemical industries, among others. Steam methane reforming (SMR), which separates hydrogen from the hydrocarbon fuel, accounts for 95% of production in the US because of its efficiency and cost advantages, with electrolysis responsible for the rest [10]. According to the NRC's report and recent US Department of Energy (DOE) planning documents, these pathways also represent the likeliest candidates for hydrogen production during the first 10 to 30 years of transition to a fully ramped-up hydrogen economy, primarily because the infrastructure for natural gas and electricity distribution are already in place, allowing for on-site distributed hydrogen generation [2, 9].

Consequently, it is expected that hydrogen production by the electrolysis of water (in which electricity is used to dissociate water into oxygen and hydrogen) along with SMR will become one of the dominant production methods of choice during the transition (i.e. over the next 10 to 30 years), with other methods such as direct biological, thermochemical or photolytic production of hydrogen potentially coming on stream as significant producers afterwards. The DOE's strategic and planning documents echo this consensus, with much emphasis on the electrolysis of water as a primary method for hydrogen production, in the near term via distributed production, and in the long term with nuclear-powered high-temperature electrolysis [2, 10–12, 17].

Though it is expected that distributed production through electrolysis and SMR will dominate the hydrogen supply market over the next 30 years, it is not clear what portion of the hydrogen production will be from SMR or electrolysis. Furthermore, because water is used directly as a feedstock or process gas for either of these pathways, their widespread use raises the question about how much water might be required for a hydrogen economy. However, because electrolysis during this transition is likely to pull from the grid, it therefore will depend in some form on thermoelectric power, and therefore will indirectly use vast amounts of water for thermoelectric cooling. Because the indirect use of cooling water in power generation is potentially so vast, the water impacts of electrolytic hydrogen production is more relevant to water resource planners. Consequently, this analysis focuses on the water intensity of hydrogen production via electrolysis 30 years into the future.

## 3. Analysis

Hydrogen production by electrolysis uses water in the following direct and indirect ways:

*Direct:* as a feedstock for hydrogen

*Indirect:* as a cooling fluid for thermoelectric generation of electricity that is needed to convey, distill and electrolyze some portion of the water that is used as a feedstock.

**Table 1.** US consumption of different liquid fuels in 2005 [18].

Fuel type	Total US consumption in 2005 (million gallons)
Gasoline	136 949
Diesel	43 180
Ethanol	3 904
Biodiesel	91

Note that the feedstock must originally be pure water, hence the requirement for distillation, whereas cooling water can be fresh or saline water and thus requires no desalting or purification. The manuscript will address the direct and indirect issues in order.

### 3.1. Quantifying demand for hydrogen

To understand the quantity of water that might be required for the hydrogen economy, an important benchmark to determine is the quantity of hydrogen that needs to be produced. The Department of Energy indicates that hydrogen will be used for transportation and portable or back-up power generation applications [2]. Because one kilogram of hydrogen has approximately the same energy content as a gallon of diesel and gasoline<sup>2</sup>, we can estimate the quantity of hydrogen that might be needed by first considering the demand for liquid fuels in the United States, shown in table 1.

Thus, if hydrogen had full market penetration as a substitute for petroleum-derived liquid fuels in 2005, it would need to replace 180 billion gallons of diesel and gasoline. Because full market penetration is not expected for many decades and hydrogen in fuel cells make more efficient use of the energy content in the fuels, it is likely that much less hydrogen will be needed. Turner estimates that 150 billion kg of hydrogen will be needed just to satisfy transportation needs in a completely scaled-up hydrogen economy [3], while Kruger used aggressive 40% year-over-year growth rates in hydrogen demand and technology improvements for transportation to calculate a demand of 104 billion kg of hydrogen in 2050 [7]. The NRC estimated that 30 years into the transition, annual demand for hydrogen might reach 60 billion kg in 2037 [9], which is the value used for the analysis contained in this manuscript.

### 3.2. Direct uses of water for electrolytic hydrogen production

In electrolytic hydrogen production, water is used directly as a feedstock. Using water's density and relative atomic populations, it is estimated by a mass balance that approximately 2.38 gallons of water are consumed as a feedstock to produce 1 kg of hydrogen gas, assuming no losses. Note for comparison that water is also used as a process gas for SMR, with 1.19 gallons of feedstock water per kilogram of hydrogen produced, assuming no losses, and an additional 3.5 gallons of water for steam production per kilogram of hydrogen produced [14].

<sup>2</sup> One kilogram of hydrogen contains approximately 120 MJ, while one gallon of diesel and gallon contains approximately 121 and 118 MJ, respectively.

Over the course of a year, this water use equates to approximately 143 billion gallons of distilled water to produce 60 billion kg of hydrogen. Overall, this amount is not much different than the water requirements for refining petroleum, which uses between 1 and 2.5 gallons of water per gallon of gasoline produced [14], and so the differences in direct water use impacts would be minimal when substituting hydrogen for traditional liquid fuels.

### 3.3. Indirect uses of water for electrolytic hydrogen production

The real difference between electrolysis, SMR and gasoline refining is the indirect water use. The indirect uses of water for electrolytic hydrogen production are primarily as a cooling liquid for thermoelectric power plants. The electricity from these plants is used to convey, treat and electrolyze water, and the overall electricity input requirements must first be determined to assess the cooling water inputs that will be needed. Conveying water can require anywhere from 0 kWh/gallon (for gravity-fed systems) to 0.014 kWh/gallon for locations such as Southern California, where the water must be moved across long distances and several mountain ranges [19]. Distilling water to remove impurities can require 0.085 kWh/gallon with industrial systems; thus it uses much more energy than conveyance. Combined, conveying and distilling water can require 0.085–0.1 kWh/gallon of feedstock water, or 0.20–0.24 kWh kg<sup>-1</sup> of hydrogen produced.

Compared with conveyance and distillation, electrolysis is far more energy intensive. For ideal conditions, the electricity input required to dissociate water into hydrogen is equal to the higher heating value (HHV) of hydrogen, which is 39.4 kWh kg<sup>-1</sup> (kilowatt hours per kilogram of hydrogen that is produced), which is hundreds of times more energy intensive than moving and treating the electrolytic feedwater. However, practical electrolyzers are not ideal. Today's systems have approximately 60–70% efficiency: the DOE has set a future target for 75% efficiency [14], and 80% or 90% efficiencies might one day be possible. Table 2 summarizes the range of electrolyzer efficiencies and electricity input requirements for dissociation of water in the two leftmost columns. Table 2 also lists the annual electricity requirements to produce hydrogen in 2037 based on the fraction of the projected 60 billion kg that is produced by electrolysis as opposed to other pathways (values from 35 to 85% are listed) and as a function of electrolyzer efficiency. If highly efficient electrolyzers are used (e.g. 90% efficient) and only 35% of the 60 billion kg of hydrogen is produced by electrolysis, then 827 billion kWh of electricity will be required annually. If inefficient electrolyzers are used (e.g. 60% efficient) and a great preponderance of the 60 billion kg of hydrogen is produced by electrolysis (e.g. 85%), then 3351 billion kWh of electricity will be required annually. Given the scale of electricity requirements for dissociation, the electricity requirements for conveyance and distillation of feedwater can effectively be ignored.

For comparison, please note that the total annual electricity generation in the US in 2005 was 4063 billion kWh [18]. Thus, producing a fraction of hydrogen

**Table 2.** Annual electricity input requirements to produce 60 billion kg of hydrogen for a varying fraction that is produced by electrolysis and a range of electrolyzer efficiencies.

Electrolyzer efficiency	Electricity required for electrolysis (kWh kg <sup>-1</sup> )	Portion of hydrogen that is produced by electrolysis					
		35%	45%	55%	65%	75%	85%
Ideal	39.4	827	1064	1300	1537	1773	2009
90%	43.8	920	1183	1445	1708	1971	2234
80%	49.3	1035	1331	1627	1923	2219	2514
75%	54.0	1134	1458	1782	2106	2430	2754
70%	56.3	1182	1520	1858	2196	2534	2871
60%	65.7	1380	1774	2168	2562	2957	3351
		Annual electricity requirements to electrolytically produce hydrogen (billion kWh)					

from electrolysis, even for very efficient systems, requires significant additional amounts of electricity to be generated.

The indirect water use that is necessary for the power plants depends on the type of power source: thermoelectric power uses water as a coolant, while renewable sources such as wind, solar and hydroelectric do not use water as a coolant. Though hydroelectric power does not use cooling water, it has high water consumption through increased evaporation at man-made reservoirs [20]. It is important to note that more than the 90% of the electricity in the US is generated through thermoelectric processes (either fossil-fuel combustion, biomass combustion, or nuclear reactions). Consequently, it can be expected that a significant fraction of power for electrolysis would be derived from thermoelectric sources that require cooling water.

According to the US Geological Survey, in 2000, thermoelectric power was responsible for about 48% of all freshwater and saline-water withdrawals in the US, requiring 195 billion gallons per day in total, and remaining roughly stable since 1985. Of those withdrawals, approximately 70%, or 132 billion gallons per day, was fresh, which is about the same amount required by the agriculture sector (predominantly for irrigation) [21]. Nearly 99% of all thermoelectric withdrawals were from surface water sources [21], with almost all of the water returned to the source without being consumed (though at a higher temperature and with a different quality) [14]. Approximately 3% (or 3.3 billion gallons per day) of the freshwater withdrawals were consumed by evaporation [14].

A comparison of the amount of water used by the thermoelectric sector in 2000 with the amount of electricity generated by thermoelectric sources in 2000 yields an average water withdrawal of 20.6 gallons per kilowatt hour for the nation's entire thermoelectric fuel mix [21, 22]. Notably, the water withdrawals and fuel mix have not changed very much between 2000 and 2005: in 2000, the total electricity generation was 3840 billion kWh, of which 90% was from thermoelectric power; in 2005, even after significant increases in wind and solar power, the total electricity generation was 4063 billion kWh, of which 90% was from thermoelectric power; and the DOE's projections out to 2030 show aggressive increases in renewable power, but also show that thermoelectric power is expected to remain 90–91% of the fuel mix [18, 22].

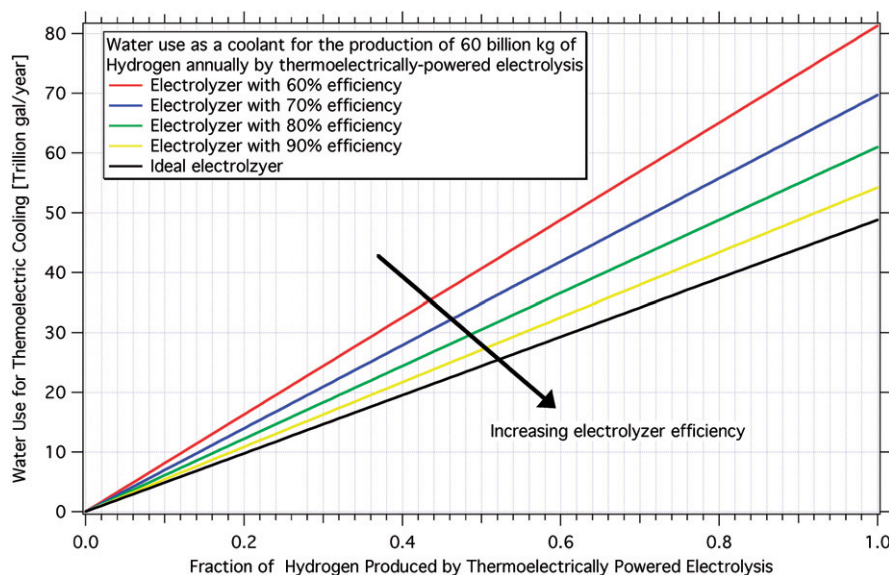
Consequently, it is reasonable to expect that some portion of the power for electrolysis will be derived from thermoelectric sources.

Note that this estimate for water withdrawals per kilowatt hour of generation is an average over geographic locations, cooling systems (e.g. once-through versus open-loop, etc), fuel sources, and power plant designs. There is significant variability of water use, however, with some thermoelectric power plants requiring up to 30–50 gallons kWh<sup>-1</sup> for once-through cooling [23]. And, as noted above, a portion of the water withdrawals for thermoelectric cooling are consumed by evaporation, typically in the range of between 0.2 and 0.72 gallons kWh<sup>-1</sup> [23]. It is also worth noting that nuclear power is often cited as a suitable carbon-free source of electricity for hydrogen production [2, 10–12, 17], but its water consumption for thermoelectric cooling is at the higher end of the typical range, at 0.4–0.72 gallons kWh<sup>-1</sup> [23]. Overall, the average US water evaporation at thermoelectric plants is 0.47 gallons kWh<sup>-1</sup> [20].

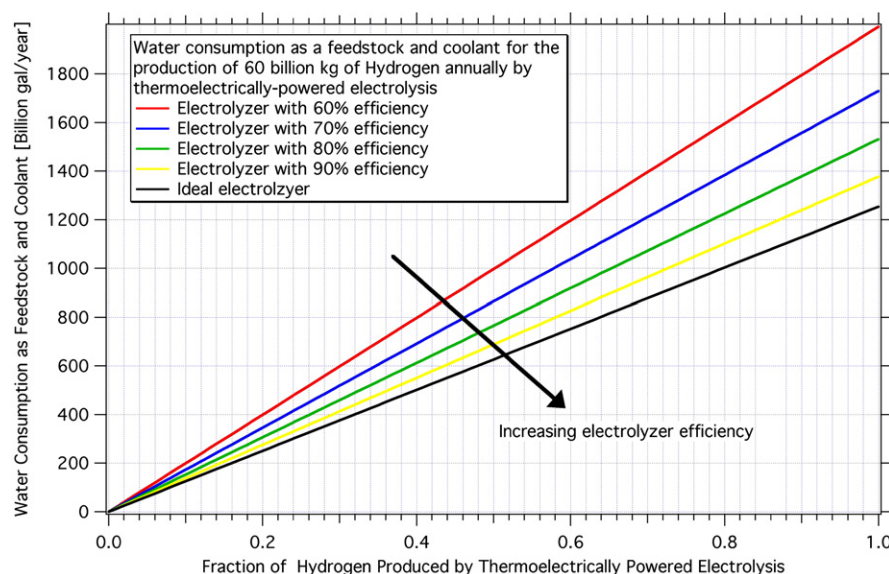
#### 3.4. Total water use for electrolytic hydrogen production

Using 20.6 gallons kWh<sup>-1</sup> of average water withdrawals for thermoelectric cooling, we can estimate the water use for hydrogen production depending on the fraction that is powered by thermoelectric sources and the electrolyzer efficiencies, as shown in figure 1 for trillions of gallons per year. On a per unit basis, thermoelectric power generation will withdraw approximately 1100 gallons of cooling water on average per kilogram of hydrogen that is produced for an electrolyzer with 75% efficiency. Using 0.47 gallons kWh<sup>-1</sup> of average water consumption for thermoelectric cooling, plus 2.38 gallons kg<sup>-1</sup> of water as a feedstock for hydrogen, we can estimate the total water consumption of hydrogen production at 60 billion kg per year, depending on the fraction that is produced by thermoelectric power and for a range of electrolyzer efficiencies, as shown in figure 2 for billions of gallons per year. On a per unit basis, thermoelectrically powered electrolysis will consume 27 gallons of water as a feedstock and coolant for every kilogram of hydrogen that is produced for an electrolyzer with 75% efficiency. As expected, as more hydrogen is produced with thermoelectric power, the total water intensity (withdrawals and consumption) increases. Furthermore, as electrolyzer efficiencies improve, the total





**Figure 1.** Annual water use as a coolant for generating 60 billion kg of hydrogen as a function of the fraction that is produced by thermoelectrically powered electrolysis and for a range of electrolyzer efficiencies.



**Figure 2.** Annual water consumption as a coolant and as a feedstock for generating 60 billion kg of hydrogen as a function of the fraction that is produced by thermoelectrically powered electrolysis and for a range of electrolyzer efficiencies.

water intensity decreases. For reference, the thermoelectric sector withdrew 72 trillion gallons of water in 2000 [21].

The total water withdrawals for thermoelectric cooling would be anywhere from 19 trillion gallons annually for 90% efficient electrolyzers if 35% of the hydrogen is produced by thermoelectrically powered electrolysis, to nearly 69 trillion gallons for electrolyzers with 60% efficiency if 85% of the hydrogen is produced by thermoelectrically powered electrolysis. These withdrawals correspond to an additional 52–189 billion gallons per day on top of the 195 billion gallons of daily withdrawals already in place for thermoelectric power, representing a potential increase of between 27 and

97%. The total water consumption would increase by between 0.5 and 1.7 trillion gallons over the course of a year for the same cases, presumably mixed 70% freshwater and 30% saline according to the existing ratios. Note that freshwater consumption in 1995 for thermoelectric applications was 1.2 trillion gallons [14].

For comparison, the reader is reminded from before that gasoline production consumes 1–2.5 gallons of water per gallon of gasoline that is produced, and hydrogen produced via SMR consumes approximately 4.6 gallons  $\text{kg}^{-1}$  of hydrogen that is produced [14], both of which are much lower than the consumption of 27 gallons of water per kilogram of

**Table 3.** Comparative values for water consumption and withdrawals during the production of gasoline and hydrogen via different pathways. Units are listed in gallons of water per gallon of gasoline for refining, and gallons of water per kilogram of hydrogen for SMR and electrolysis [2, 20].

Fuel	Production pathway	Water consumption (gal kg <sup>-1</sup> ) or (gal/gal)	Water withdrawals (gal/gal) or (gal kg <sup>-1</sup> )
Gasoline	Refining	2.5	2.5
Hydrogen	Steam methane reforming	4.6	4.6
Hydrogen	Electrolysis (thermoelectric)	27	1100
Hydrogen	Electrolysis (hydroelectric)	950	—

hydrogen for electrolyzers with 75% efficiency operated by average thermoelectric power. Switching to hydroelectric power for electrolysis, which consumes 18 gallons kWh<sup>-1</sup> due to increased evaporation at man-made reservoirs [20], would increase the water consumption to approximately 950 gallons of water per kilogram of hydrogen that is produced with electrolyzers operating at 75% efficiency. Note that withdrawals for hydroelectric power are considered to be zero by convention. These values are summarized in table 3.

Consequently, if the hydrogen economy includes thermoelectrically or hydroelectrically powered electrolysis as a prominent source of hydrogen, then we can expect significant increases in water withdrawals and consumption for fuel production over today's use of gasoline. Given that water withdrawals have remained steady for decades, these increases in water use represent a significant potential impact on a critical resource.

#### 4. Conclusions

Hydrogen production using thermoelectric powered electrolysis is significantly more water intensive than gasoline production. If 60 billion kg of hydrogen are manufactured a year by electrolysis, it will consume approximately 143 billion gallons of water just as the feedstock. Furthermore, because electrolysis is a very energy-intensive process, manufacturing 60 billion kg of hydrogen annually with that method would require vast amounts of electricity. Since thermoelectric power makes up 90% of the fuel mix in the US, it is likely that some portion of that power for electrolysis will consequently require significant amounts of water for cooling.

Using recent data for water withdrawals by the thermoelectric sector and overall energy consumption, it can be deduced that the water withdrawal and consumption increases for a thermoelectrically powered hydrogen economy are significant. The calculated water withdrawals for electrolytic hydrogen production could increase by anywhere from 27 to 97%, depending on electrolyzer efficiencies from 60 to 90% and the fraction that is produced by thermoelectric power (from 35 to 85%), while consumption (including evaporative losses and conversion of feedwater into hydrogen) might increase by 0.5–1.7 trillion gallons per year. On a per unit basis, thermoelectric power generation for electrolysis will on average withdraw approximately 1100 gallons of cooling water and will consume 27 gallons of water as a feedstock and coolant for every kilogram of hydrogen that is produced using an electrolyzer that has an efficiency of 75%.

Given that water withdrawals have remained steady for decades, this increase in water use represents a significant potential impact of the hydrogen economy on a critical resource, and thus presents a serious technical and public policy problem. If minimizing the impact of water resources is a priority and electrolysis becomes a widespread method of hydrogen production, it is likely that the power for electrolytic hydrogen production will have to come from non-thermoelectric, non-hydroelectric and non-irrigated renewable sources. Consequently, almost all the new electricity generating capacity for hydrogen production would need to be from hydrogen production pathways that do not use much water (such as wind or solar), or effective water-free cooling methods (e.g. air cooling) will need to be developed and widely deployed.

#### References

- [1] Bush G W 2007 Address before a joint session of the congress on the state of the union *Weekly Compilation Presidential Documents* **43** 8
- [2] USDOE 2006 *Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan* United States Department of Energy
- [3] Turner J A 2004 Sustainable hydrogen production *Science* **305** 972–4
- [4] Wald M L 2004 Questions about a hydrogen economy *Sci. Am.* **290** (5) 66–73
- [5] Kreith F 2004 Fallacies of a hydrogen economy: a critical analysis of hydrogen production and utilization *J. Energy Res. Technol.* **126** 249–57
- [6] Romm J 2005 *The Hype About Hydrogen: Fact and Fiction in the Race to Save the Climate* (New York: Island Press)
- [7] Kruger P 2006 *Alternative Energy Resources: The Quest for Sustainable Energy* (Hoboken, NJ: Wiley)
- [8] Mason J E 2007 World energy analysis: H<sub>2</sub> now or later? *Energy Policy* **35** 1315–29
- [9] Committee on Alternatives and Strategies for Future Hydrogen Production and Use, National Research Council 2004 *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (Washington, DC: National Academies Press)
- [10] USDOE 2002 *A National Vision of America's Transition to a Hydrogen Economy—To 2030 and Beyond* United States Department of Energy
- [11] USDOE 2002 *National Hydrogen Energy Roadmap* United States Department of Energy
- [12] USDOE 2004 *Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan* United States Department of Energy
- [13] Bogart S L 2002 Comparison of investment and related requirements for selected hydrogen vehicle system pathways *J. Fusion Energy* **21** 181–91

- [14] USDOE 2006 *Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water* United States Department of Energy
- [15] Paul J 2006 *Experts: Ethanol's Water Demands a Concern: Biofuel Plants' Impact on Aquifers Eyed by Scientists* (MSNBC.com: Associated Press)
- [16] Keeney D and Muller M 2006 *Water Use by Ethanol Plants: Potential Challenges* (Minneapolis, MN: Institute for Agriculture and Trade Policy)
- [17] USDOE 2004 *Nuclear Hydrogen R&D Plan* United States Department of Energy
- [18] USDOE 2007 *Annual Energy Outlook 2007: With Projections to 2030* US Department of Energy, Energy Information Administration
- [19] 2005 *California's Water-Energy Relationship: Final Staff Report, in Prepared in Support of the 2005 Integrated Energy Policy Report Proceeding* California Energy Commission
- [20] Torcellini P, Long N and Judkoff R 2003 *Consumptive Water Use for US Power Production* Golden, CO, National Renewable Energy Laboratory, US Department of Energy
- [21] Hutson S S *et al* 2004 *Estimated Use of Water in the United States in 2000* (Reston, VA: US Geological Survey)
- [22] USDOE 2002 *Annual Energy Outlook 2002: With Projections to 2020* US Department of Energy, Energy Information Administration
- [23] 2003 *Power Generation Water Use in Texas for the Years 2000 Through 2060: Final Report* Texas Water Development Board